Collaborative Research: Regulating Hazardous Materials Transportation by Multi-Objective Dual Toll Pricing

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Hazardous Materials (hazmat)

Network Design Approach to Hazmat Transportation

- Regulator’s objective is to minimize the system-wise risk by closing certain road segments to hazmat vehicles
- Carrier’s objective is to reduce transportation cost under the regulation

(Single) Toll System Approach to Hazmat Transport

- Marcotte et al. (2009)
- Regulator’s objective is to minimize the system-wise risk by charging tolls to hazmat vehicles
- Carrier’s objective is to reduce transportation cost under the toll policy
- (No congestion) (No impact of regular traffic)

Dual Toll Pricing

- Motivation: travel delay of hazmat traffic is related to regular traffic
- To achieve safe network flow, by appropriate control of regular traffic flows
- We consider a dual toll pricing system for both regular traffic and hazmat trucks at the same time.

Risk Measure and Travel Delay

- We consider a duration-population-frequency risk measure:
  \[ R_d(v, u_a) = s_a(v_a)\rho_u u_a \]
  where \( \rho_u \) is the population exposure along the arc.
- The linear travel delay function is:
  \[ s_a(v_a) = t_a(1 + v_a/C_a) \]

MPEC Formulation

\[
\begin{align*}
\min_{w, v, t, u_a} & \quad J = w_1 R(v, u)^T 1_A + w_2 [s(v)]^T v + w_3 [s(v)]^T u \\
\text{subject to} & \quad (s(v) + \alpha)^T (t - v) \geq 0 \quad \forall t \in V \\
& \quad (s(v) + \beta)^T (u - v) \geq 0 \quad \forall v \in V \\
& \quad u \in U \\
& \quad \alpha, \beta \geq 0
\end{align*}
\]

Case Study for Albany, NY (46 nodes and 70 arcs)

Results

<table>
<thead>
<tr>
<th>(w_1, w_2, w_3)</th>
<th>Risk</th>
<th>Delay (regular)</th>
<th>Delay (hazmat)</th>
<th>Toll (regular)</th>
<th>Toll (hazmat)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10^{-4}, 1, 1)</td>
<td>25.96%</td>
<td>22.61%</td>
<td>39.61%</td>
<td>3.25 x 10^{-3}</td>
<td>1.96 x 10^{-3}</td>
</tr>
<tr>
<td>(1, 1, 1)</td>
<td>25.70%</td>
<td>22.61%</td>
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<td>5.29 x 10^{-3}</td>
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</table>

Simulation Approach

- To design a micro evaluation model with interrelationship among carrier companies, government, and individual driver’s behavior.
- An agent-based simulation approach based on the Extended Belief-Desire-Intention (BDI) framework to mimic behaviors of different driver agents.

An Evaluation Framework with Simulation

AnyLogic Simulation Modeling

Next Steps

- Optimization Approach considering Stochastic Behavior of Drivers
- Dynamic Model with static intervals
- Fully Dynamic Model considering Stochastic Behavior of Drivers

Objectives

- To investigate the potential of dual toll pricing as an operational tool to reduce risk from hazardous materials (hazmat) transportation in our society.
- Key Research Questions:
  - Can we implement a multi-objective toll policy to reduce the risk induced by hazmat trucks, while preserving the travel efficiency of both hazmat trucks and regular commuting vehicles?
  - Will such a multi-objective toll policy encourage hazmat carriers to utilize time periods with less traffic?
  - Will such a toll policy be robust enough to protect our community from various uncertainties arising in traffic networks, incidents, environments, etc?
  - How should the equity issue between geographic and demographic zones be addressed, to ensure that any single zone does not have a disproportionately large number of hazmat transports?
  - What is the best way to validate a toll policy, while reflecting realistic random behavior of drivers?

Mode of Hazmat Shipment in 2007

<table>
<thead>
<tr>
<th>Mode</th>
<th>Value(%)</th>
<th>Tons (%)</th>
<th>Ton-miles(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck</td>
<td>57.8</td>
<td>53.3</td>
<td>32.2</td>
</tr>
<tr>
<td>Rail</td>
<td>4.6</td>
<td>5.8</td>
<td>29.5</td>
</tr>
<tr>
<td>Water</td>
<td>4.8</td>
<td>6.7</td>
<td>11.5</td>
</tr>
<tr>
<td>Air</td>
<td>0.1</td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td>Pipeline</td>
<td>27.2</td>
<td>28.2</td>
<td>small</td>
</tr>
</tbody>
</table>

Number of hazmat incidents in 2000-2009

<table>
<thead>
<tr>
<th>Mode</th>
<th>No. of Incidents</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>13,232</td>
<td>7.89</td>
</tr>
<tr>
<td>Highway</td>
<td>146,120</td>
<td>87.09</td>
</tr>
<tr>
<td>Rail</td>
<td>7,987</td>
<td>4.76</td>
</tr>
<tr>
<td>Water</td>
<td>446</td>
<td>3.27</td>
</tr>
<tr>
<td>Total</td>
<td>167,785</td>
<td>100</td>
</tr>
</tbody>
</table>

How to Control Network Flows?

- Network Design Approach
  - Close/Open road segments
  - Increase capacity of road segments
- Toll System Approach
  - Charge tolls to vehicles traveling certain road segments

Review of Congestion Toll Pricing

- Optimally choose toll pricing policy:
  - to minimize the total travel delay
  - subject to user behavior based on (travel delay + toll)